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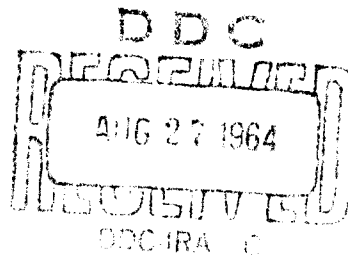
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Environmental Research Papers
No. 19



Crater Frequency and the Interpretation of Lunar History

ROBERT T. DODD, Jr.
JOHN W. SALISBURY
VERN G. SMALLEY



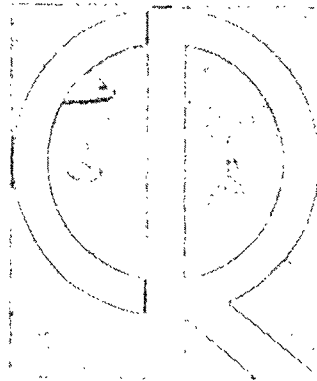
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Crater Frequency and the Interpretation of Lunar History

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The significance of lunar crater frequencies as a function of crater diameter has been investigated. We conclude that the absolute ages of isochronous surfaces previously determined by this technique are not valid. Relative ages can be obtained from crater frequencies when account is taken of complications caused by secondary and, perhaps, igneous craters, and obliteration of old craters by younger ones. Studies made at AFCRL indicate that the maria are of similar, but not identical ages, and that some maria may contain surfaces of different ages. They also indicate that the Apenninian debris sheet is older, but not much older, than the maria. The present surface of the crater Ptolemaeus is evidently composed of either Apenninian debris, or Procellarian material. We conclude that crater frequency is a useful stratigraphic tool.

INTRODUCTION

Several writers have discussed the use of crater frequencies to date lunar surfaces. Most of these (Öpik, 1960; Kreiter, 1960; Shoemaker *et al.*, 1961) have concentrated on absolute dating, and in particular, on dating the widespread Procellarian mare material. A minority (e.g., Palm and Strom, 1963) have used crater frequency as a stratigraphic indicator.

The data needed to translate crater frequencies into absolute ages are many (Shoemaker *et al.*, 1961), but the most critical are a value for the present meteoroidal flux and for the changes in this flux during lunar history. Estimates of the present flux (Brown, 1960 and 1961; Millard, 1963) differ widely (Millard's result is forty-five times that of Brown, 1960, and fifteen times that of Brown, 1961), as do opinions on the constancy or inconstancy of the flux. Although crater frequency is potentially useful for absolute dating of lunar surfaces, the mare ages reported to date by Öpik (1960), Kreiter (1960), and Shoemaker *et al.* (1961) can-

not be accepted for want of reliable calibration.

Assuming no area selectivity, relative dating of surfaces by crater frequencies does not require assumptions regarding the present and past meteoroidal fluxes. It is, in principle, a simple and valuable stratigraphic tool. This paper reports an attempt to develop this tool and apply it to several lunar stratigraphic problems. (A summary of previous work in lunar stratigraphy is presented in Appendix I.)

BASIS OF RELATIVE AGES DETERMINED BY CRATER FREQUENCIES

Of two surfaces exposed to the same flux of meteoroids and to no other crater-forming processes, that which shows the greater crater density (number of craters per unit area) is the older. Several cases can be recognized:

(1) If the total flux and size distribution of meteoroids are constant throughout the histories of both surfaces, curves of cumulative frequency of craters versus crater diameter for the two surfaces will

be parallel and will differ by a constant. As Kreiter (1960) notes, this special case permits determination of the absolute age of the younger surface, if the age of the older surface is known.

(2) If the total flux of meteoroids has changed, but their size distribution has not, the cumulative frequency-diameter curves will still be parallel but their difference in position will no longer be a simple function of age difference.

(3) If the size distribution of meteoroids has changed, the curves will not be parallel, but the older surface will still show the higher frequency.

We believe that case (2) probably approximates the natural situation. In principle, then, plots of cumulative frequency versus diameter for various lunar surfaces should unequivocally indicate the sequence of formation of these surfaces.

In practice, many factors modify the ideal case, viz.: (1) errors in the frequency curves caused by the small samples necessary to study of small areas; (2) flux differences associated with position on the Moon due to gravitational focusing (Shoemaker *et al.*, 1961); (3) obliteration of old craters by younger ones; (4) interruption of cratering through partial or total cover-

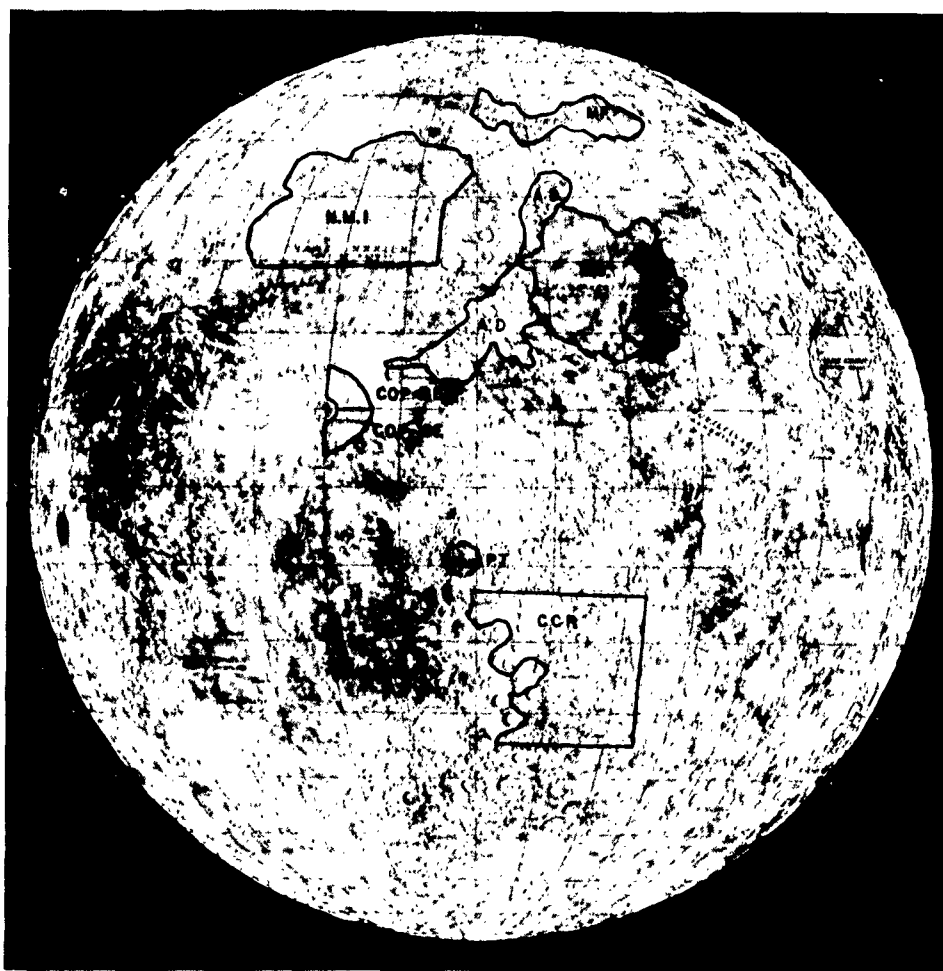


FIG. 1. USAF lunar reference mosaic, showing areas in which craters were counted for this study. Letter symbols are as given in Table I.

ing of a cratered surface; and (5) addition to the number of primary craters by secondary and igneous craters. The first and fourth factors do not seriously affect any of the surfaces discussed in this paper. The others are dealt with in connection with the lunar surfaces to which they pertain.

Data

Crater diameters were measured on several lunar surfaces which, because of uni-

form topography, albedo, and relationships to other terranes, are thought to be isochronous. These surfaces are outlined on the index map (Fig. 1) and listed in Table I. Techniques of measurement and the estimated uncertainties are discussed in Appendix II to this paper.

The cumulative frequency-diameter data for the surfaces were subjected to a least-squares treatment on the AFCRL I.B.M. 7090 computer by L. M. Sylvia and Allan

TABLE I
LUNAR SURFACES ON WHICH CRATERS HAVE BEEN COUNTED

Surface	Symbol Fig. 1	Area (km ²)	A ^a	B ^a	R ^{2 a}
Mare Frigoris	MF	1.6×10^5	1299.0	-1.545	0.969
Mare Serenitatis	MS	3.4×10^5	641.7	-1.707	0.977
Light portion	MS-Light	2.6×10^5	561.6	-1.702	0.959
Dark portion	MS-Dark	8.5×10^4	581.2	-1.535	0.939
Northern Mare Imbrium	NMI	4.7×10^5	1172.6	-1.776	0.985
Apenninian debris	AD	1.3×10^5	9661.8	-2.103	0.989
Central Crater Province	CCP	3.4×10^5	49 687.0	-2.085	0.943
Ptolemaeus	PT	1.3×10^4	5072.3	-2.118	0.961
NE of Copernicus	COP-NE	3.5×10^4	488 317.0	-4.804	0.956
SE of Copernicus	COP-SE	3.1×10^4	439 110.0	-4.629	0.918

^a A and B are constants in the expression relating diameter and crater frequency; R² is the correlation coefficient (squared) for the computed diameter-frequency curves. See text.

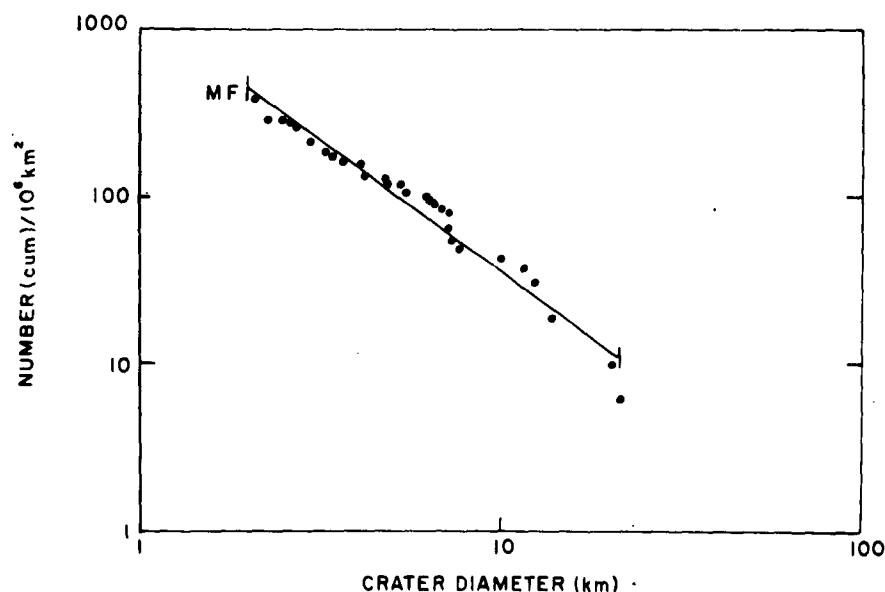


FIG. 2. Crater frequency (cumulative) as a function of crater diameter for part of Mare Frigoris. Data and computed curve are shown.

Whittaker of AFCRL. The relationship between frequency and crater diameter was found to be best approximated by the relationship: $F = AD^B$, where D is the crater diameter (kilometers), F is the cumulative frequency (number of craters of diameter D per 10^6 square kilometers), and A and B are constants, the latter negative. Values of A , B , and the square of the correlation coefficient, R , are given in Table I for each surface. The observations and computed curves are shown in Figs. 2 through 11.

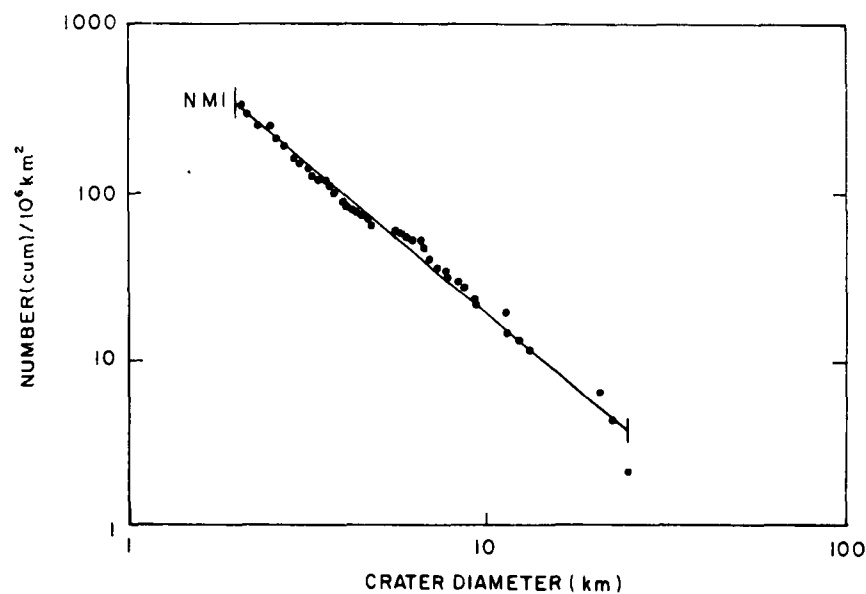


FIG. 3. Crater frequency (cumulative) as a function of crater diameter for Northern Mare Imbrium. Data and computed curve are shown.

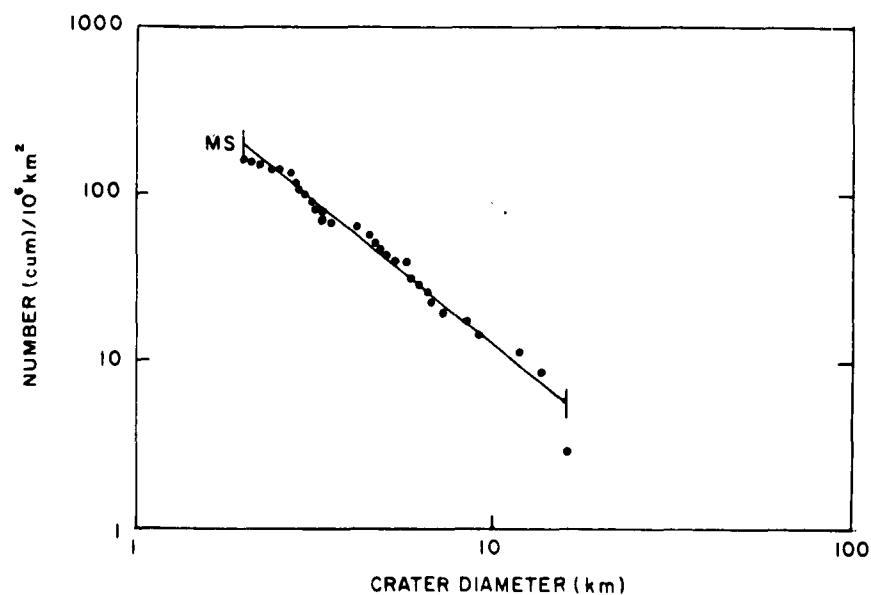


FIG. 4. Crater frequency (cumulative) as a function of crater diameter for Mare Serenitatis. Data and computed curve are shown.

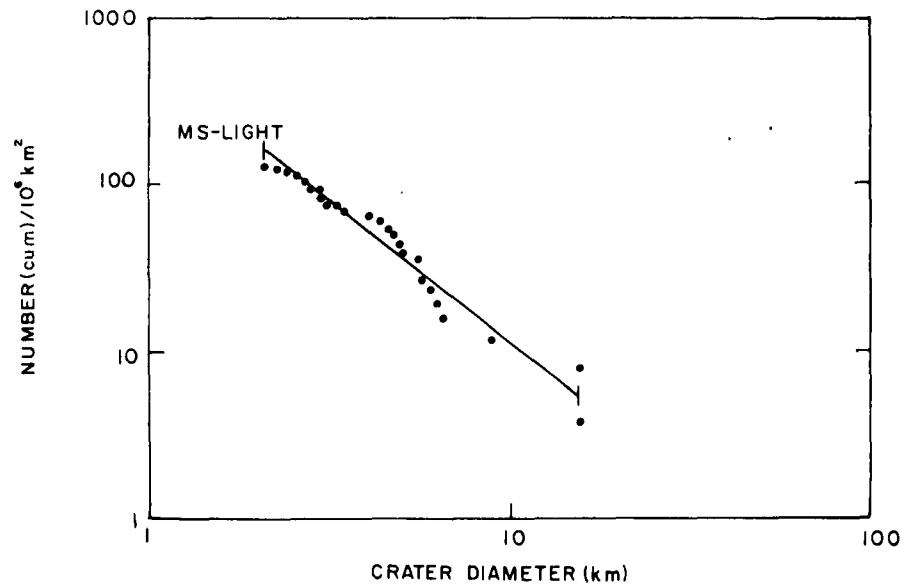


FIG. 5. Crater frequency (cumulative) as a function of crater diameter for light terrane in Mare Serenitatis. Data and computed curve are shown.

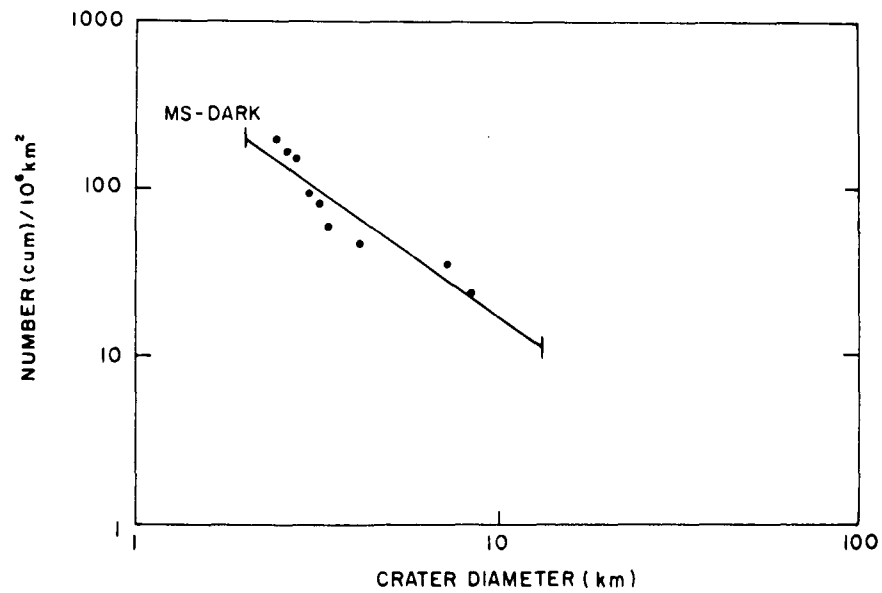


FIG. 6. Crater frequency (cumulative) as a function of crater diameter for dark terrane in Mare Serenitatis. Data and computed curve are shown.

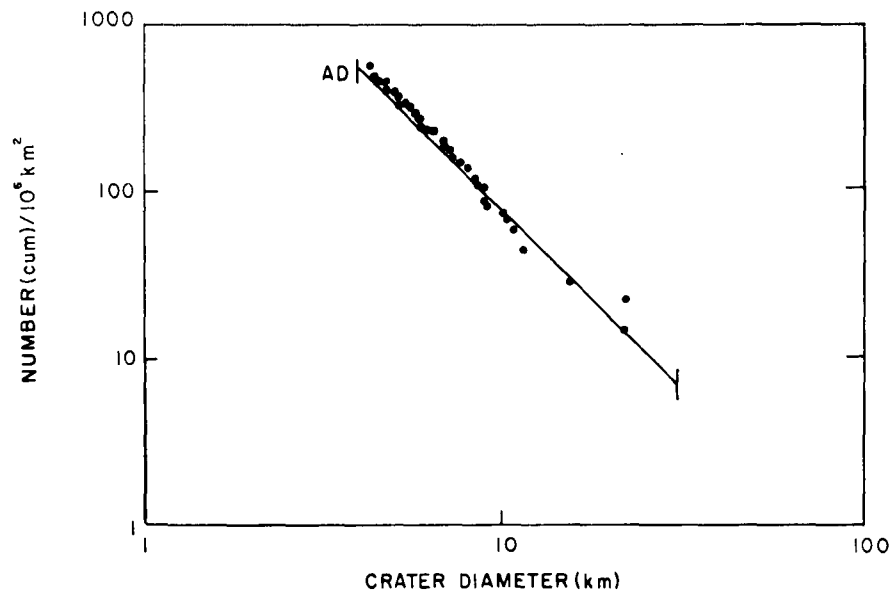


FIG. 7. Crater frequency (cumulative) as a function of crater diameter for Apenninian debris sheet. Data and computed curve are shown.

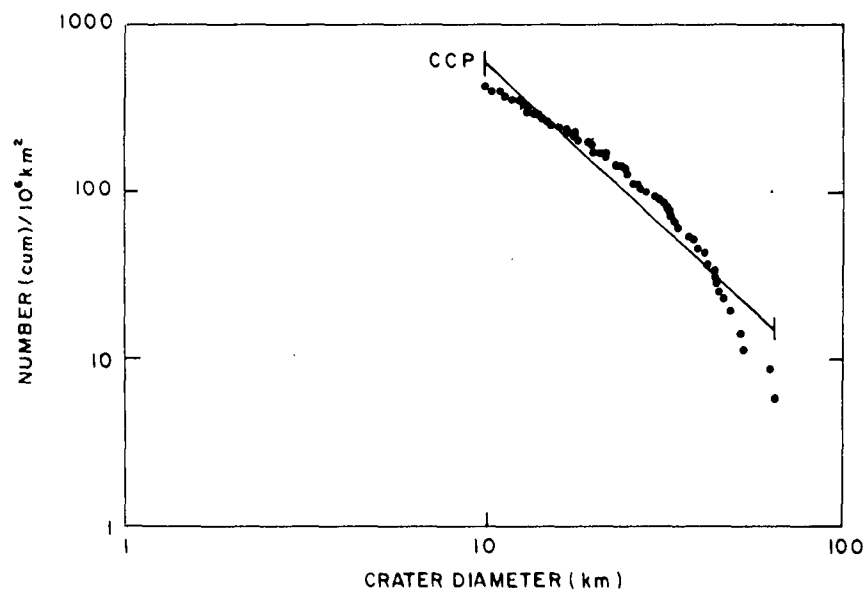


FIG. 8. Crater frequency (cumulative) as a function of crater diameter for part of the Central Crater Province. Data and computed curve are shown.

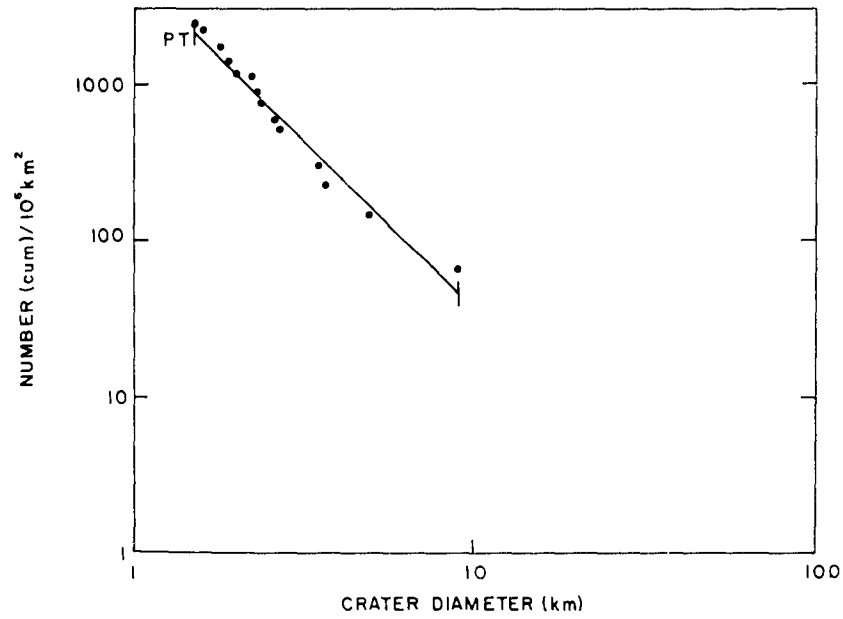


FIG. 9. Crater frequency (cumulative) as a function of crater diameter for present surface of Ptolemaeus. Data and computed curve are shown.

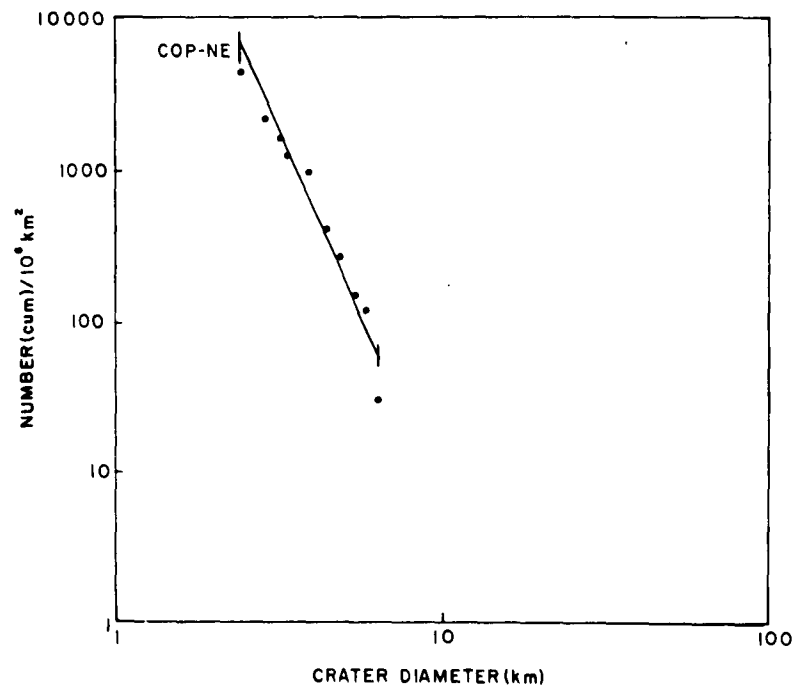


FIG. 10. Crater frequency (cumulative) as a function of crater diameter for area northeast of Copernicus. Data and computed curve are shown.

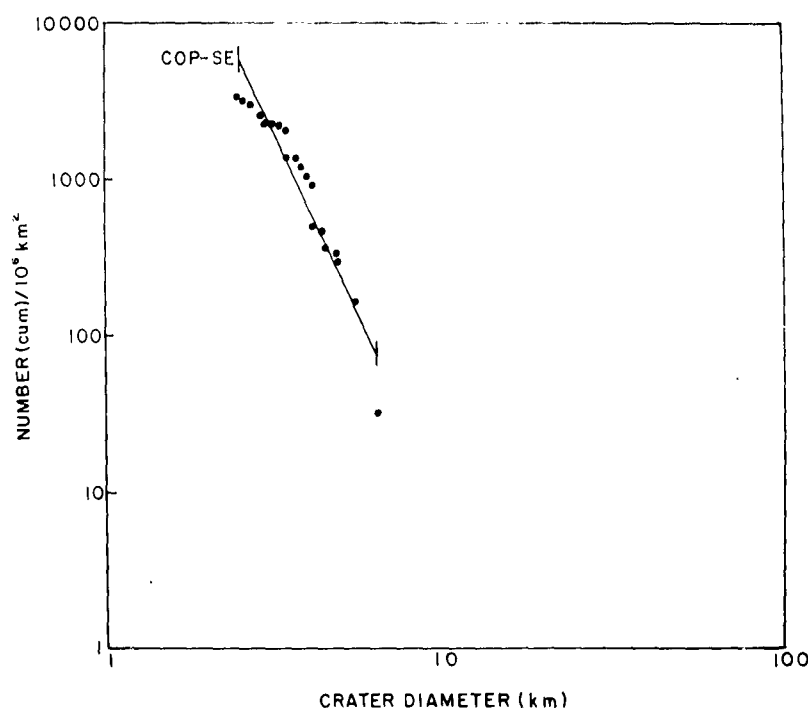


FIG. 11. Crater frequency (cumulative) as a function of crater diameter for area southeast of Copernicus. Data and computed curve are shown.

RELATIVE AGES OF ADJACENT MARE SURFACES AND THE APENNINIAN DEBRIS

Crater frequencies for three mare surfaces and the Apenninian debris sheet are compared in Fig. 12. The raw data (Figs. 2, 3, 4 and 7) indicate that the samples obtained from the areas studied are large enough to be meaningful, and the surfaces are close enough together to preclude major frequency differences due to nonuniform distribution of the meteoroidal flux over the lunar surface (see discussion in Shoemaker *et al.*, 1961).

As one would expect from the overlap of the three maria on the debris, the maria have lower crater frequencies than the debris and are thus younger. The mare curves have similar slopes (values of B) but differ considerably with respect to A . As the differences among them are too large to be accounted for by observational error (estimated as $\pm 18\%$ of A —see Appendix), we conclude that the three maria are of

somewhat different ages and that the Procellarian system can be subdivided on the basis of crater frequency.

Figure 12 and Table I show that the slope of the Apenninian debris curve is steeper than the slopes for the mare curves. We believe the debris curve is steepened by a component of secondary craters caused by the fall-back of large blocks ejected by the great impact that formed the central Imbrium basin. This mechanism is discussed further for the Ptolemaic surface; it suffices to note here that subtraction of the secondary craters from the debris curve would make it more nearly parallel to, and nearer to, the mare curves.

It is appropriate to stress here that the mare curves in Fig. 12 are averages for large areas, and that these areas may, and probably do, consist of subareas of different ages. This point is illustrated by Mare Serenitatis which contains two terranes: dark material near the margin and lighter

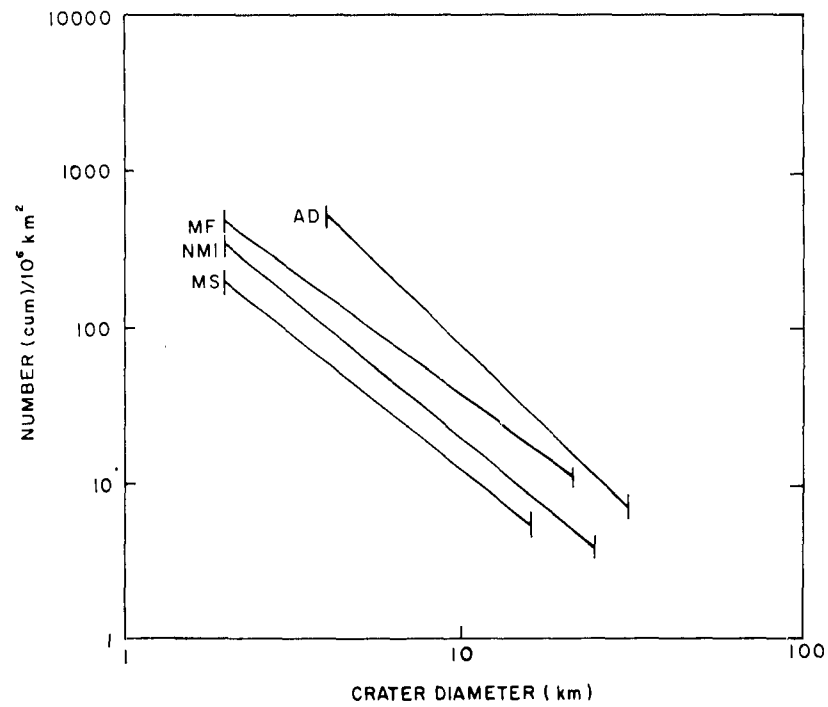


FIG. 12. Crater frequencies (cumulative) as a function of crater diameter for Mare Frigoris (MF), Mare Serenitatis (MS), northern Mare Imbrium (NMI), and the Apenninian debris sheet (AD). Vertical bars indicate degree of uncertainty.

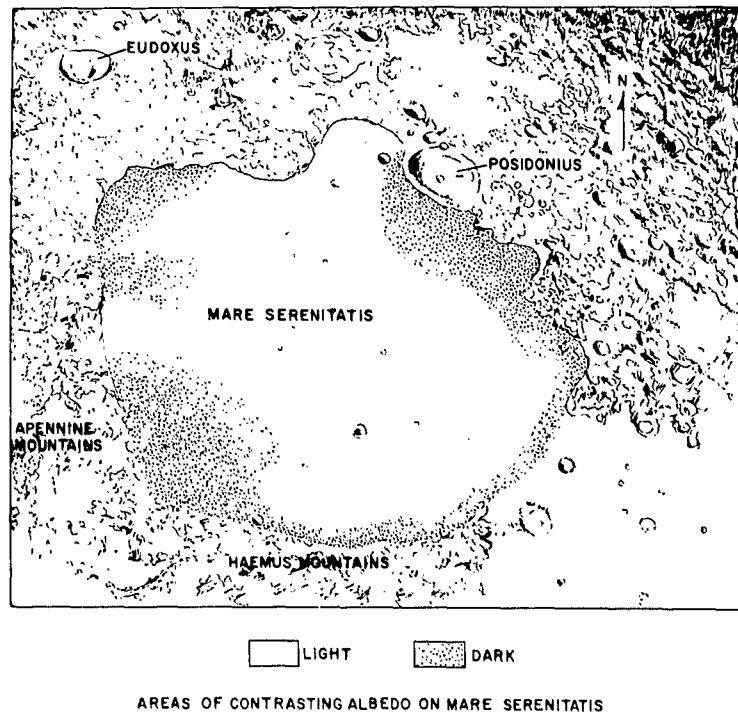


FIG. 13. Outlines of light and dark areas (the latter stippled) on M. Serenitatis.

material near the center (see Fig. 13; also Plates B3-C and C3-C of the "Lunar Atlas," Vol. 1, Kuiper, 1960). The results of crater measurements on the two terranes (Fig. 14) suggest a slight age difference

many types of terranes are present (Hackman and Mason, 1961). We selected a portion of the Central Crater Province (Hackman and Mason, 1961) for comparison with the maria. The comparison is not in-

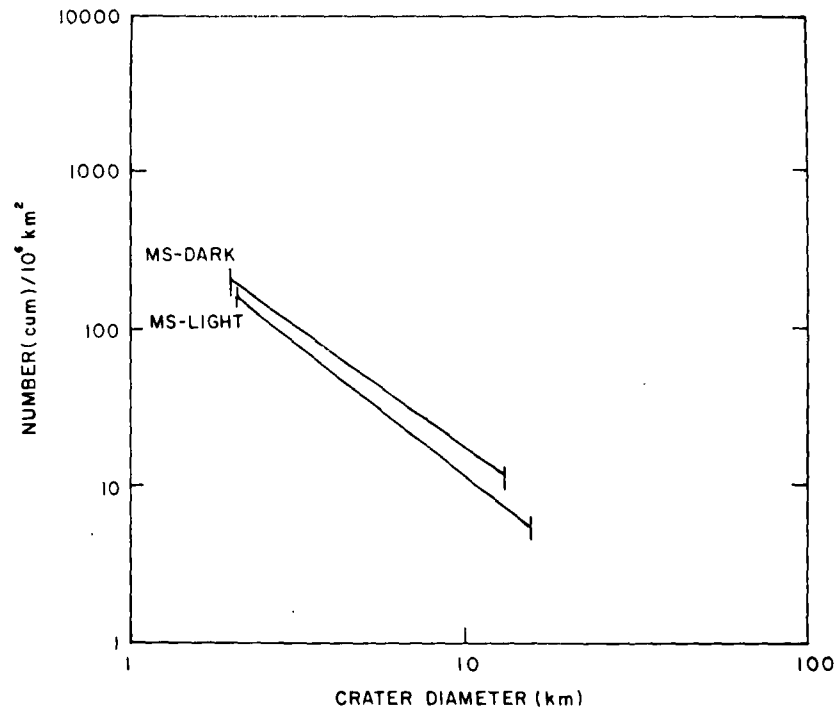


FIG. 14. Crater frequencies (cumulative) as a function of crater diameter for light and dark terranes of Mare Serenitatis. Vertical bars indicate degree of uncertainty.

between them, but the data (Figs. 5 and 6) are too poor for certainty because of the small samples available. Differences in color and albedo among and within the maria have long been recognized (see review by Fielder, 1961; also Baldwin, 1949, p. 213, on Mare Imbrium); as better photography enhances our ability to recognize and measure small craters (and hence to work with smaller surfaces), it may be possible to subdivide the Procellarian system into many smaller compositional and stratigraphic units.

SIGNIFICANCE OF THE HIGHLANDS CURVE

No single area of the highlands is representative of the highlands as a whole, as

tended to demonstrate the relative ages of the highlands and maria, which are evident from overlap relations, but rather to determine whether frequency curves for the highlands are similar to, or different from, those for the maria.

Figure 15 suggests that the curves for the Central Crater Province and Mare Frigoris are essentially parallel. In this case, however, the raw data (Figs. 2 and 8) are more instructive than the computed curves. Although the data for Mare Frigoris are well approximated by the computed curves, the Central Crater Province data depart strongly from the form, $F = AD^B$. The reason for this is obvious from a study of the Lunar Atlas Plate (Playfair,

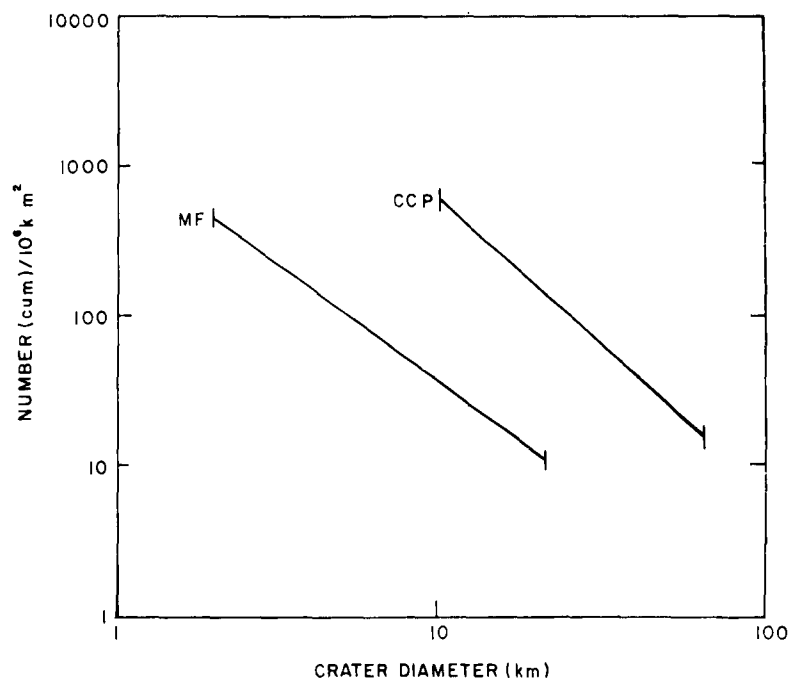


FIG. 15. Crater frequencies (cumulative) as a function of crater diameter for parts of M. Frigoris (MF) and the central crater province (CCP). Vertical bars indicate degree of uncertainty.

Sheet C6-A) on which the craters were measured. Many craters have been nearly destroyed by younger impacts. In some cases, vague circular patterns in the rough terrain suggest obliterated craters. It appears that where a surface has been completely riddled with craters, the visible craters are only a fraction of those which have been present. The observed frequency-diameter curve is then of the form $F = AD^B f$, where f is an expression (at present unknown) which is due chiefly to obliteration of old craters and, in part, to secondary impacts. That the maria curves obey the simpler relationship $F = AD^B$ is due to the large separation of craters on the maria.

The practical result of these considerations is that measurements of crater frequencies in intensely cratered areas are subject to very large uncertainties, and that the use of the ratio of crater frequencies on the highlands and maria to date the

latter (Kreiter, 1960) involves large errors in addition to those introduced by assuming a constant meteoroidal flux.

THE SURFACE OF PTOLEMAEUS: EFFECT OF SECONDARY CRATERS

Ptolemaeus is one of several large craters adjacent to Mare Nubium in which Eggleton and Marshall (1962) have identified apparently pre-Imbrian marelike material which is thought to carry a veneer of fine Apenninian debris. We attempted to date this veneer by measuring craters in the present (veneer) surface of Ptolemaeus, exclusive of ghost craters on the underlying surface. The resulting size frequency curve is given in Fig. 16, along with the curves for M. Frigoris and the Apenninian debris.

The slope of the Ptolemaeus curve ($B = -2.118$) is clearly steeper than the other curves. The difference is greater than can be explained by experimental error and

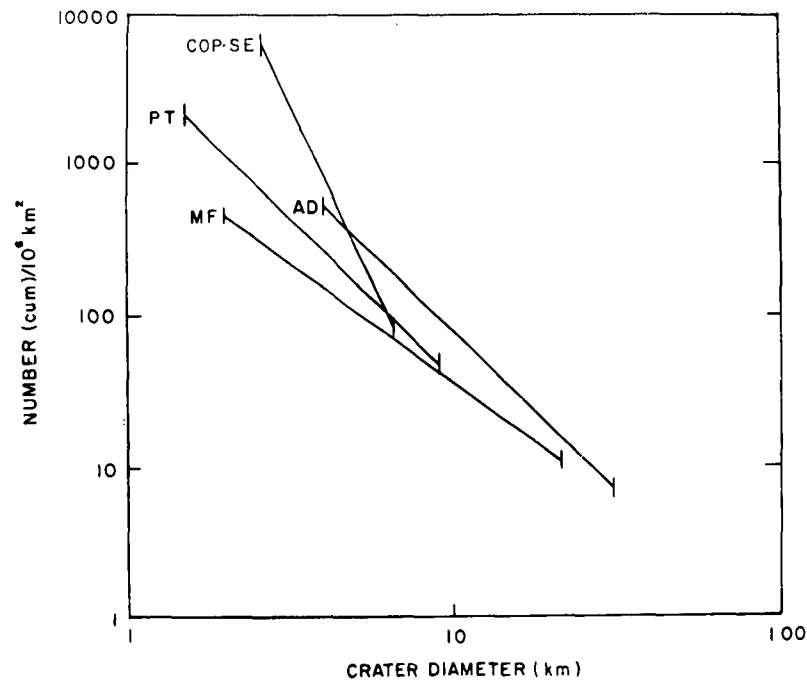


FIG. 16. Crater frequencies (cumulative) as a function of crater diameter for part of M. Frigoris (MF), the present surface of Ptolemaeus (PT), the Apenninian debris (AD), and an area just southeast of Copernicus (COP-SE). Vertical bars indicate degree of uncertainty.

indicates, we believe, that the Ptolemaic surface carries more than one type of crater. Primary meteoroidal craters are one type represented. The remainder are then either secondary meteoroidal craters, igneous craters (Palm and Strom, 1963), or both.

To test the hypothesis that secondary craters produced by debris ejected from primary impact craters can account for the steepness of the Ptolemaeus curve, we measured crater diameters in two areas thought to be populated chiefly by secondaries: the areas just northeast and southeast of Copernicus (Fig. 1). The curves for these areas (Figs. 10, 11, and 16) are much steeper than those for the other surfaces studied, but of the same form, namely: $F = AD^B$. A combination of one of the mare curves with one of Copernicus curves would produce a curve of intermediate slope such as that observed for Ptolemaeus. Because at least one of the Copernicus

curves (COP-NE) contains chain craters of probable internal origin in addition to secondary craters, we cannot rule out the occurrence of igneous craters on Ptolemaeus; however, secondary craters alone can account for the observed size distribution. The source of secondary bodies may have been Copernicus or Tycho, or nearer craters such as Herschel.

As was noted in an earlier section of this paper, the Apennine debris curve also appears to be abnormally steep. In this case, crater measurements extend to only 4 km, and there are no craters nearby which are large enough to account for secondaries of this size. We suggest that the steepness of this curve is due to a component of secondary craters formed by late-arriving ejecta from the immense impact which produced the central Imbrian basin and Apenninian debris sheet (Baldwin, 1949).

Clearly the presence of secondary craters in the Ptolemaeus and Apenninian debris

curves complicates the use of these curves as stratigraphic indicators. However, the secondary craters affect only the smaller sizes for each curve. The large diameter ends of the curves probably approximate the frequencies for impact craters alone. On this basis, Fig. 16 suggests that, within the limits of the crater frequency technique, the ages of the Ptolemaic surface, Apenninian debris, and Mare Frigoris are the same or nearly the same. Thus the surface of Ptolemaeus may consist of either Apenninian debris, as proposed by Eggleton and Marshall (1962) or of early Procellarian material. The latter might be volcanic ash which, like fine debris, would mantle pre-existing craters without wholly obscuring them.

SUMMARY OF CONCLUSIONS

The relative abundances of craters on different lunar surfaces can be used to determine the relative ages of these surfaces, but the technique is complicated by secondary and igneous craters and, in the highlands, by obliteration of old craters by younger ones. Translation of relative ages into absolute ages requires a knowledge of the present meteoroidal flux and its variation in the past, and is not now possible.

A comparison of crater frequencies on the surfaces of Mare Imbrium, Mare Frigoris, and Mare Serenitatis indicates that these mare surfaces are of similar but not identical ages. In addition, different terranes within the maria appear to be of different ages. The Apenninian debris sheet is older than the mare surfaces, but the difference in age appears to be small.

When account is taken of secondary and, perhaps, igneous craters in the surfaces of the Apenninian debris and Ptolemaeus, these surfaces appear to be of essentially the same age as that of Mare Frigoris. The veneer which covers Ptolemaeus is probably either fine Apenninian debris or early Procellarian volcanic ash.

Within the restrictions discussed above, crater frequency is a valuable tool for the lunar stratigrapher, and one whose value

will increase when better photographic resolution permits the study of smaller areas.

APPENDIX I

Lunar Stratigraphy

The two great lunar physiographic divisions, the maria and the highlands, have relative ages which are clearly indicated by overlapping of the former on the latter. Each of these major divisions is in turn composed of a variety of surface materials whose physical interrelationships, topographic expressions, and photometric properties can be used to establish their relative ages. A lunar stratigraphic column based on these data was proposed by Shoemaker *et al.* (1961) and Hackman (1962), and extended by Eggleton and Marshall (1962). This column is summarized in Table II.

TABLE II
THE LUNAR STRATIGRAPHIC COLUMN

Hackman (1962)	This paper
Copernican System	Copernican System
Eratosthenian System	Eratosthenian System
Procellarian System	Procellarian System
Imbrian System	
Archimedian Series	Archimedian Series
Apenninian Series	Apenninian Series
	Pre-Imbrian System
	Ptolemaic Series ^a
	Highlandian Series ^a

^a These terms are as used in the present paper; the series were identified, but not named by Eggleton and Marshall (1962).

Before the publication of Eggleton and Marshall's work, the Imbrian system was considered to be the oldest extensive stratigraphic unit in this sequence. It consists of a basal, sheetlike unit of regional extent (the Apenninian series) which forms the Apennine Mountains and surrounding Apenninian debris (see Fig. 1). The crater-rim and crater-floor materials of craters on the Apenninian series comprise the

Archemedian series of the Imbrian system. The Apenninian series is usually interpreted as a sheet of debris from the Imbrian impact crater, and the Archemedian series as the ejecta sheet and interior debris of meteorite craters which were superimposed on the Apenninian debris before the appearance of the Procellarian system. The Procellarian system consists of material of low albedo and low relief which overlies parts of the Imbrian system and fills the maria and Oceanus Procellarum. It is thought to consist of lavas or tuffs, and is overlain by still younger craters. These craters are divided into two generations, the older producing the crater-rim and crater-floor deposits of the Eratosthenian system (named after the crater Eratosthenes), and the younger producing the similar deposits of the Copernican system (named after the Crater Copernicus). Rays are found only around the Copernican craters, presumably because the ray materials darken with time.

Eggleton and Marshall (1962) have defined a pre-Imbrian system, which includes the highlands crater-rim and crater-

APPENDIX II

A. Method of Obtaining Lunar Areas Used in Calculation of Crater Frequency Curves

Regions of interest on the lunar surfaces were first outlined in the "Lunar Atlas," Vol. 1 (Kuiper, 1959) and then divided into sectors, each sector being assigned an average selenographic longitude, λ , and latitude, β , determined from the "Lunar Atlas," Vol. 2 (Kuiper, 1960). The area of each sector was measured directly from Vol. 1 of the "Lunar Atlas," and multiplied by its respective value of secant λ , secant β . The products were then summed to obtain the true area.

$$\text{True area} = \sum_{i=1}^{i=n} \text{Area}_i \secant \lambda_i \secant \beta_i$$

for a region divided into n sectors.

The true area, measured in square inches from Vol. 1 of the "Lunar Atlas," was then multiplied by $(1.21) \times 10^3$ to yield the true area of the region in square kilometers.

The areas of the regions of interest were found to be as shown in the table.

Surface	Area (Km ²)	Number of sectors in area, n	Normalization factor
Mare Frigoris (East)	(1.62)10 ⁵	17	6.18
Mare Serenitatis	(3.4)10 ⁵	40	2.9
Mare Imbrium (North)	(4.7)10 ⁵	36	2.13
Apenninian Debris	(1.3)10 ⁵	6	7.45
Central Crater Province	(3.4)10 ⁵	14	2.9
Ptolemaeus	(0.13)10 ⁵	1	74.4
Copernicus (NE Sector)	(0.35)10 ⁵	1	28.9
Copernicus (SE Sector)	(0.31)10 ⁵	1	32.2

floor deposits (named here the Highlandian series) and younger marelike material which forms relatively smooth plains or plateaus adjacent to the maria and partly fills a few older craters such as Ptolemaeus. This older marelike material is named here the Ptolemaic series. Small craters which occur on this series are partly mantled by relatively smooth material which Eggleton and Marshall interpret as Apenninian debris.

B. Sources of Error

In calculating the true areas of the sectors, both longitudinal and latitudinal libration (which vary throughout the plates in Vol. 1 of the "Lunar Atlas") were disregarded. Neglect of the variation in libration resulted in a maximum error of 12% in the calculation of the true area. The error in actual measurement of the areas in the "Lunar Atlas" was less than 4%, and counting errors are estimated to be

2%. Thus, the estimated total error in the vertical placement of points shown in Figs. 2 through 11 is 18%. This error is reflected in the length of the vertical segment at each end of the straight line which is drawn through the plotted points.

The correlation coefficient, R , is defined as follows:

$$R = \frac{n \sum x_i y_i - \sum x_i \sum y_i}{\{[n \sum x_i^2 - (\sum x_i)^2][n \sum y_i^2 - (\sum y_i)^2]\}^{1/2}}$$

where

n = total number of data points;

X_i = \log_{10} (crater diameter);

y = \log_{10} (normalized cumulative crater number).

As noted in Table I, the square of the correlation coefficient differs for the data from the various lunar surfaces. R^2 is a measure of the confidence in fitting the equation $Y = AX^B$ to the data.

C. Measurement of Crater Diameters

Diameters were measured on plates of the "Lunar Atlas" (Vol. 1, Kuiper, 1959). All measurements were made parallel to the limb and were converted from millimeters to kilometers using a constant scale factor of 1 mm = 1.37 km. The error anticipated for a given measurement varies somewhat with the size and irregularity of the crater and crater rim. It is probably as much as ± 2 mm (± 2.74 km) for large craters having diameters of about 50 km. Such errors in individual measurements do not appreciably affect the slope and position of the cumulative curves.

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